Design, Contact Modeling, and Collision-inclusive Motion Planning of Dual-Stiffness Aerial RoboT(DART)

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Research statement

Physical interactions with the environment are often leveraged by both humans and animals to navigate efficiently through congested spaces. This research work explores whether aerial robots can similarly improve their navigation by incorporating collisions into their trajectory planning. To investigate this, we developed a dual-stiffness collision-resilient aerial robot equipped with a locking mechanism that allows it to switch between flexible and rigid modes. Moreover, we designed a control and planning framework that generates and follows collision-inclusive trajectories.

System Characterization

Locking mechanism

The relationship between l and Θ is defined as follows:

$$l = R - r\cos(\Theta) \qquad (1)$$

$$\Theta_i \leq \Theta \leq (\Theta_i + 90^o) \qquad (2)$$

$$l_f - l_i = 10\,mm \qquad (3)$$

where R and r are cam and rotational circle radius, respectively.

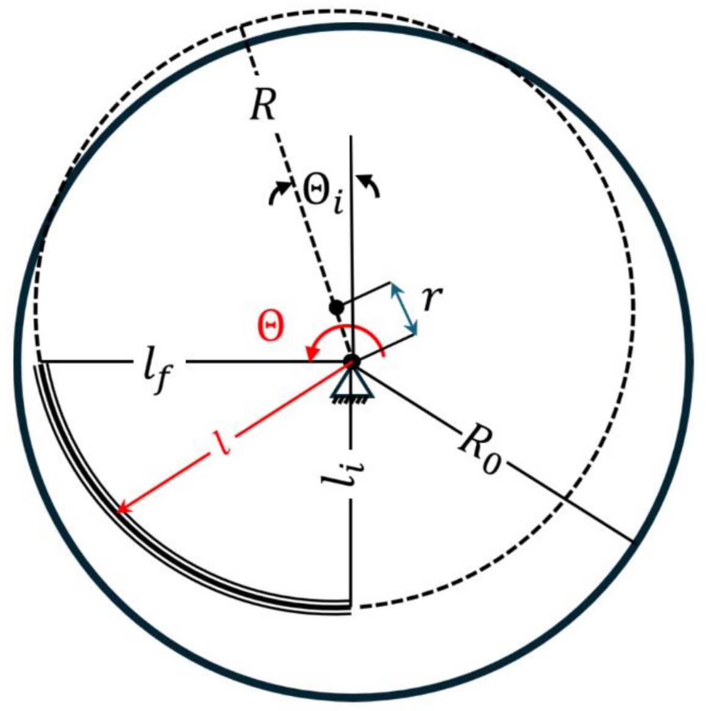


Fig. 1 Four-face cam mechanism

Drop tests

- We collected data by performing drop tests to model the collision dynamics
- Drop heights 5cm and 20cm were considered to have an impact velocity of 1m/s and 2m/s respectively.

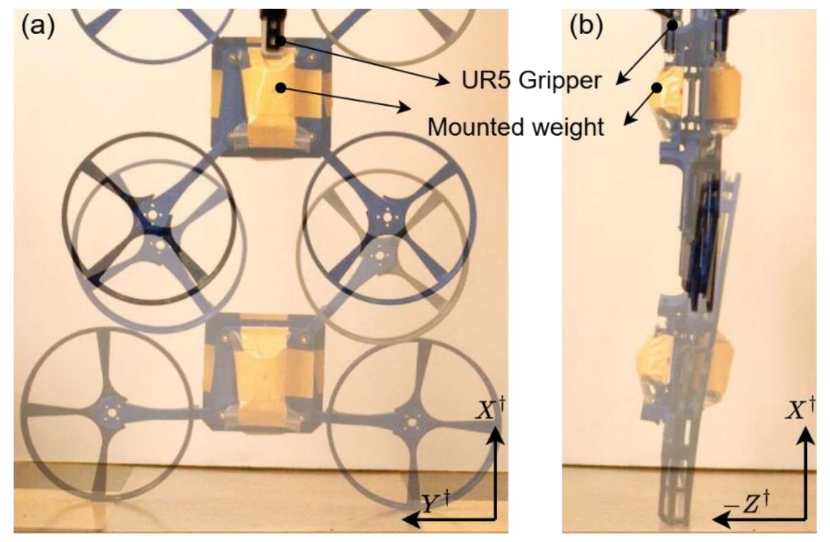


Fig 2. Drop test experimental setup

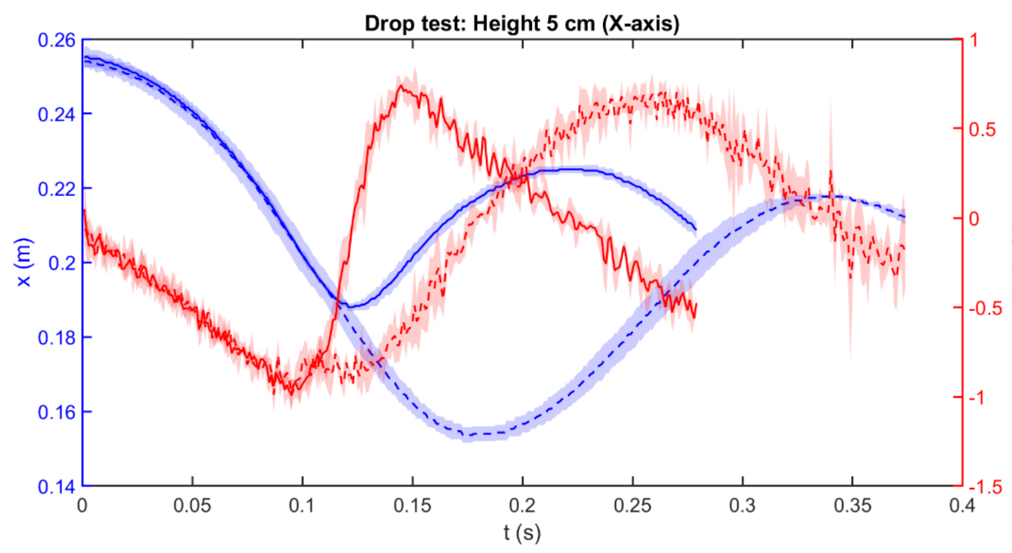


Fig 3. Drop test result (height 5cm)

Contact Modeling

LCS formulation

A 3D point mass with spring-damper at point of collision

Assumption: Propeller guards are aligned with obstacle

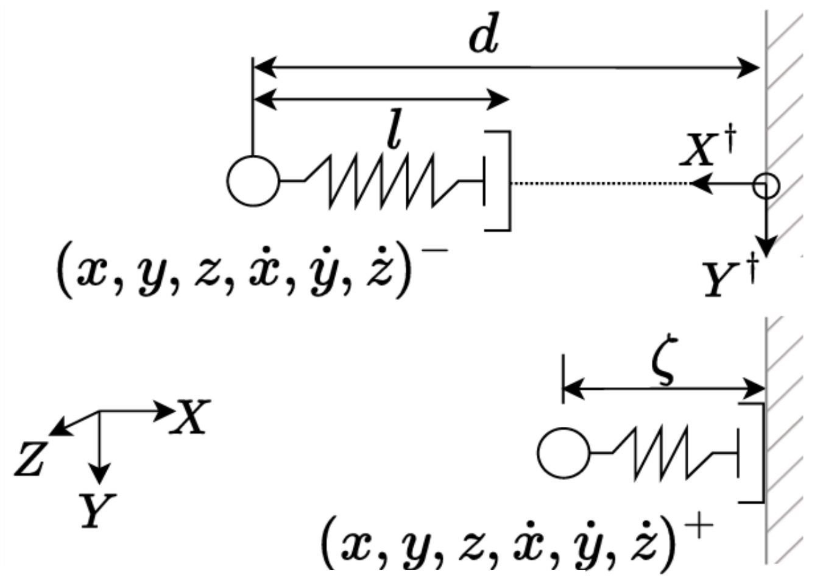
$$\ddot{x} = g(\boldsymbol{u}) + diag(b)\dot{\boldsymbol{x}} \qquad (4)$$

$$\dot{\bar{\boldsymbol{x}}} = A\bar{\boldsymbol{x}} + B\bar{\boldsymbol{u}} + \bar{\boldsymbol{\lambda}} \qquad (5)$$

$$\bar{\boldsymbol{x}} = [x, \dot{x}] \text{ and } \bar{\boldsymbol{u}} = [0_3, u] \in \mathbb{R}^6$$

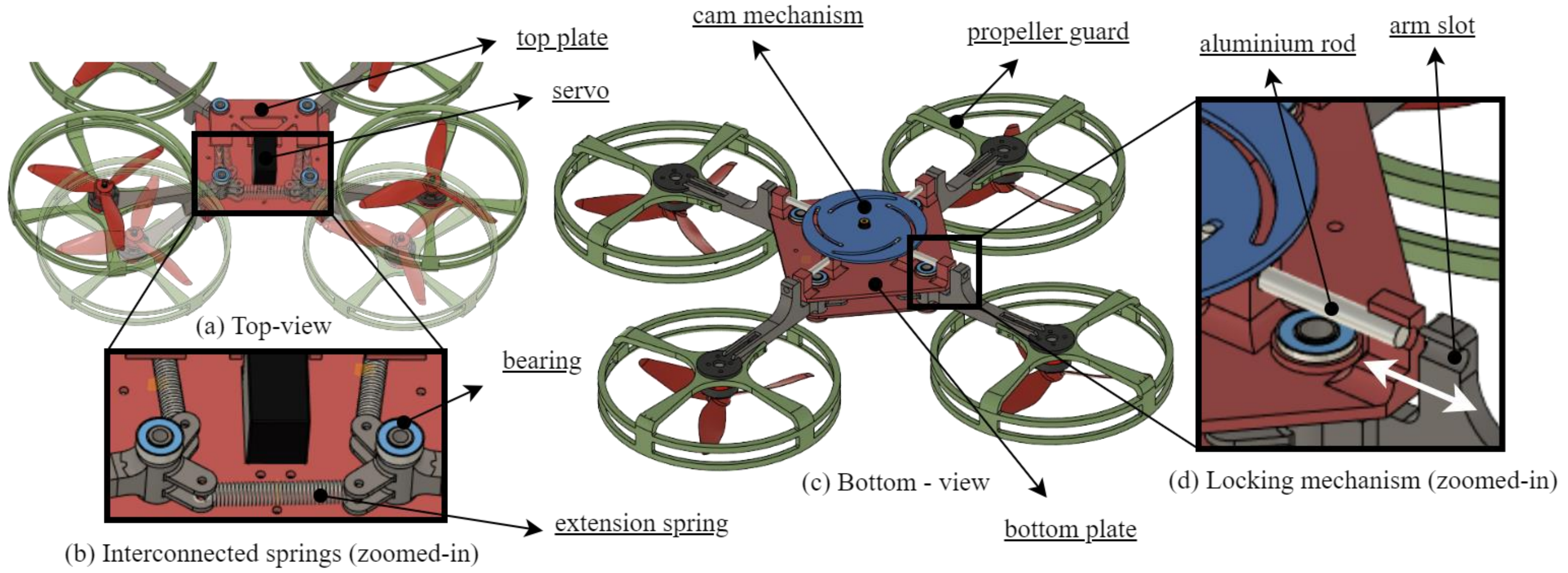
$$\bar{\boldsymbol{\lambda}} = [0_3, R^\dagger \lambda] \in \mathbb{R}^6 \; ; \lambda = [\lambda_{x^\dagger}, \lambda_{y^\dagger}, \lambda_{z^\dagger}] \; ; \; R^\dagger \in \mathbb{R}^{3\times3}$$

$$0 \leq \lambda_{x^\dagger} \perp w(x^\dagger, \lambda_{x^\dagger}) = \lambda_{x^\dagger} + kx^\dagger + f\dot{x}^\dagger \geq 0 \qquad (6)$$



$$\left.\begin{array}{l} \lambda_{y^\dagger} = -\mu\lambda_{x^\dagger}\dot{y}^\dagger \\ \lambda_{z^\dagger} = -\nu\dfrac{\lambda_{x^\dagger}}{1+\lambda_{x^\dagger}} \end{array}\right\} \text{empirically derived}$$

Design



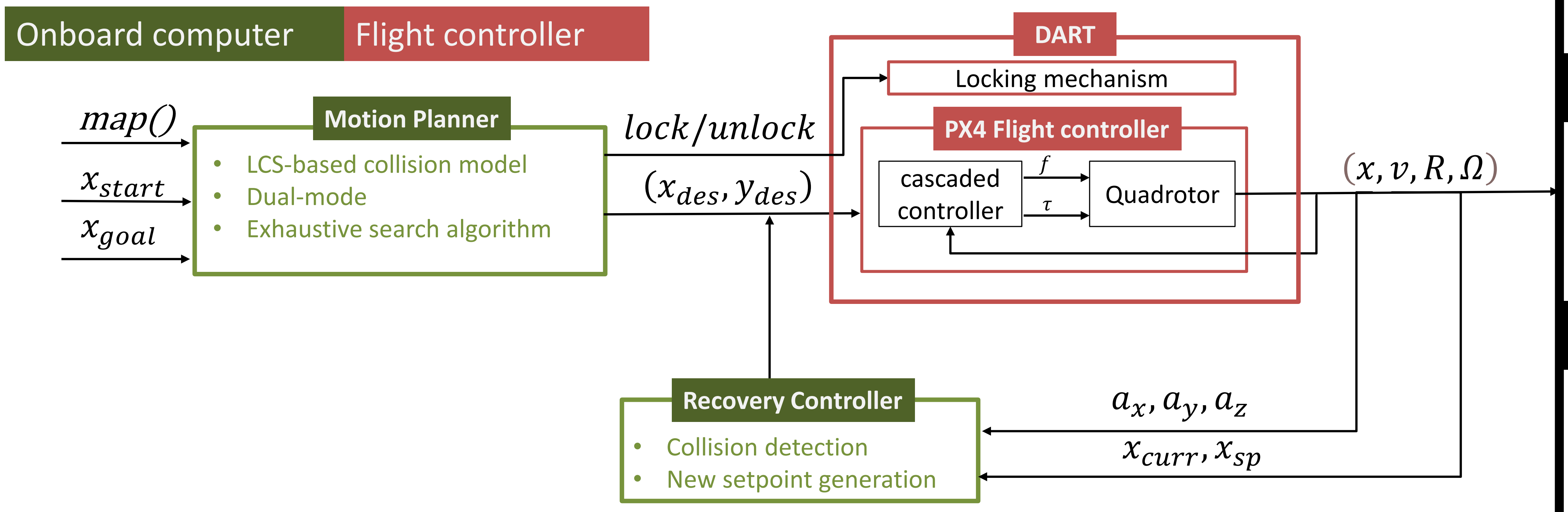
(a) Top-view

(b) Interconnected springs (zoomed-in)

(c) Bottom - view

(d) Locking mechanism (zoomed-in)

Control and Planning



Motion Planner
- LCS-based collision model
- Dual-mode
- Exhaustive search algorithm

Recovery Controller
- Collision detection
- New setpoint generation

Results

- Validates collision model and recovery controller
- Shows mode-switching capability
- Contact force prediction accuracy - 88% (flexible) and 82% (Rigid) and it depend on the following things
  - Unmodelled moments
  - Control input to stabilize
  - k, f, μ and ν material property

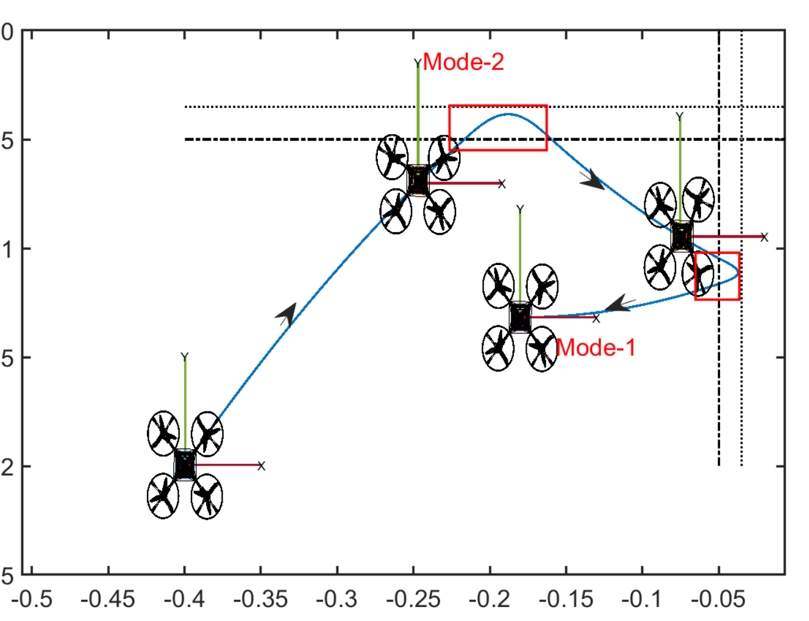
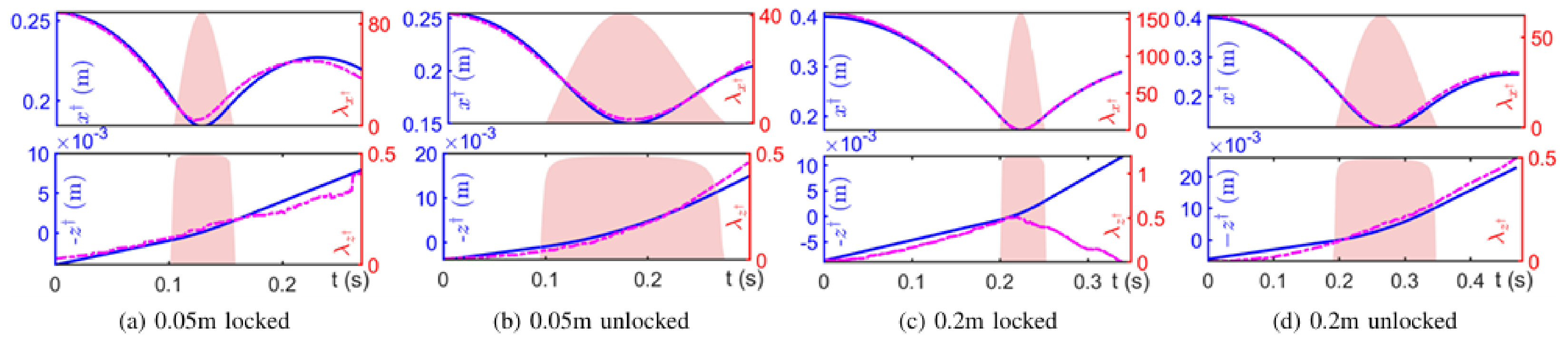


Fig. 4 Dual-collision experiment



(a) 0.05m locked (b) 0.05m unlocked (c) 0.2m locked (d) 0.2m unlocked

Fig. 5 Model fit results for drop tests (blue). Drop tests experimental data (magenta). Predicted contact force (shaded red region)

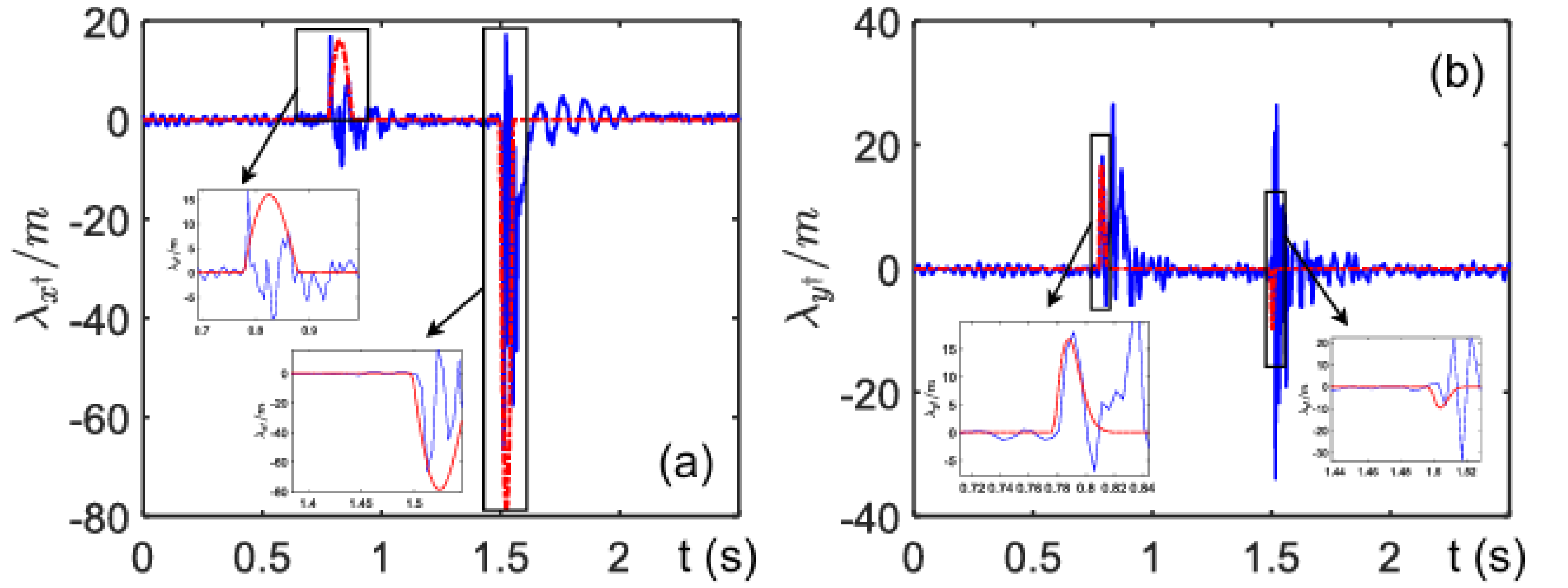


Fig. 6 Experimental results of dual-collision experiment, first collision in flexible mode and second in rigid mode as shown in Fig. 4

Future Work

- 3D collision-resilient frame design and modeling (active control of stiffness of 3D cage)
- Incorporate collision dynamics model with system dynamics to develop an optimal controller or trajectory planner

References

1. Patnaik, K., Saravanakumaran, A. A. P., & Zhang, W. (2023). To Collide or Not To Collide–Exploiting Passive Deformable Quadrotors for Contact-Rich Tasks. *arXiv preprint arXiv:2305.17217*
2. K. Patnaik, S. Mishra, S. M. R. Sorkhabadi and W. Zhang, "Design and Control of SQUEEZE: A Spring-augmented QUadrotor for intEractions with the Environment to squeeZE-and-fly," 2020 IEEE/RSJ IROS, Las Vegas, NV, USA, 2020

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